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Cost and Performance Report

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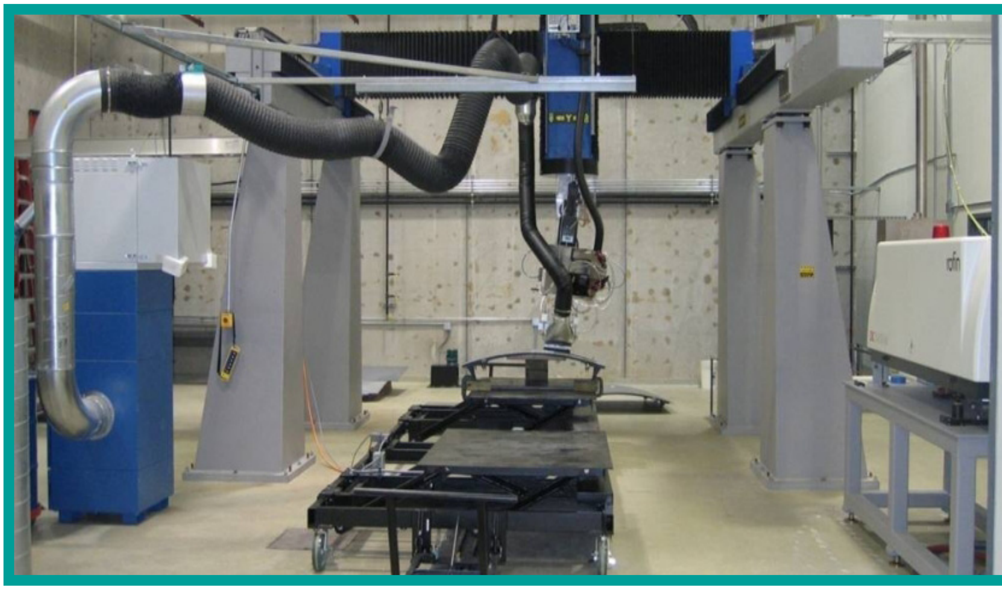

Robotic Laser Coating Removal System

August 2008

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ESTCP Project: WP-0526

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (continued)

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AFOSH	Air Force Occupational Safety and Health
AFRL	Air Force Research Laboratory
ALC	Air Logistics Center
ANSI	American National Standards Institute
BRIC	Building Research Infrastructure & Capacity
CAA	Clean Air Act
CO_2	carbon dioxide
COTS	commercial off-the-shelf
CTC	Concurrent Technologies Corporation
CWA	Clean Water Act
DoD	Department of Defense
EC	environmental compliance
ECAM	Environmental Cost Analysis Methodology
EHS	Environmental Health and Safety
ESTCP	Environmental Security Technology Certification Program
HAP	hazardous air pollutant
He	helium
HQ AFMC	Headquarters Air Force Materiel Command
in-lbf/in	inch-pound force per inch
IRR	internal rate of return
JTP	Joint Test Protocol
ksi	kips per square inch
kW/cm^2	kilowatt per square centimeter
LARPS	Large Area Robotic Paint Stripping
Laser	light amplification by stimulated emission of radiation
LSO	laser safety officer
m/s	meter(s) per second
mil	thousandth(s) of an inch (0.001 inches)
min	minute(s)

ACRONYMS AND ABBREVIATIONS (continued)

N_2	nitrogen
NADEP JAX	Naval Air Depot at Jacksonville
NAVAIR	Naval Air Systems Command
Nd:YAG	neodymium:yttrium-aluminum garnet
NPV	net present value
OC-ALC	Oklahoma City Air Logistics Center
OEM	original equipment manufacturer
OMB	Office of Management and Budget
OSHA	Occupational Safety and Health Administration
PLCRS	Portable Handheld Laser Small Area Supplemental Coating Removal System
PPE	personal protective equipment
PSOA	Process Specific Opportunity Assessment
RCRA	Resource Conservation and Recovery Act
RFP	request for proposal
RLCRS	Robotic Laser Coating Removal System
RXSA	Materials Integrity Branch
RXSC	Acquisition System Support Branch
SERDP	Strategic Environmental Research and Development Program
UDRI	University of Dayton Research Institute
USAF	U.S. Air Force
USEPA	U.S. Environmental Protection Agency

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- University of Dayton Research Laboratory (UDRI)
- Headquarters Air Force Materiel Command (AFMC)
- Concurrent Technologies Corporation (CTC)
- Naval Air Systems Command (NAVAIR)
- Naval Air Depot at Jacksonville (NADEP JAX)

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1.0 EXECUTIVE SUMMARY

Current methods for the removal of Department of Defense (DoD) coating systems from on-equipment and off-equipment components are costly, time consuming, labor-intensive, and result in undesirable environmental conditions. Large quantities of hazardous waste are commonly generated from these depot-related activities and are typically subjected to high disposal costs and scrutiny under environmental regulations. The wastes that are associated with coatings removal include the disposal of liquid paint removers and contaminated rinse water from chemical stripping operations and media waste from a variety of blasting processes. Chemical paint removers are the only process currently authorized for removing paint from KC-135 aircraft and components. In 2007, Tinker Air Force Base (AFB) reported using approximately 4360 gallons of chemical paint removers and generated approximately 2.7 million gallons of contaminated rinse water from the stripping of KC-135 candidate components alone.

Coatings removal activities are impacted by regulations promulgated under the Clean Water Act (CWA), Clean Air Act (CAA), and Resource Conservation and Recovery Act (RCRA). Washing surfaces following depainting operations can generate quantities of wastewater contaminated with methylene chloride or media and paint residue. Discharging wastewater with traces of hazardous waste can result in a direct violation of the CWA. The most common regulations associated with depainting activities are those issued under the CAA, including the recent efforts to minimize the use of hazardous air pollutants (HAP) such as methylene chloride. RCRA directly regulates disposal of wastes generated by depainting activities. RCRA regulates how and where depainting waste can be disposed and transported as well as any future liabilities resulting from environmental damage.

Because of these environmental concerns, all branches of DoD currently involved in coatings removal operations are concerned with identifying alternative methodologies focused primarily toward eliminating or reducing chemical paint strippers, dry media blasting, and hand sanding. As a result, the Robotic Laser Coating Removal System (RLCRS) has been identified as an alternative technology to the current chemical and mechanical methods that are used to remove coatings from large off-equipment aircraft components at the Air Logistics Centers (ALC).

This project was built on two previous Strategic Environmental Research and Development Program (SERDP) projects, PP-139 Laser Cleaning and Coatings Removal and PP-134 Large Area Robotic Paint Stripping (LARPS), which were undertaken to automate the coatings removal process. Available documentation for these projects was reviewed, and personnel involved in the projects were interviewed to gain an understanding of the technical difficulties encountered and gather lessons learned to help ensure successful completion of this project. Process engineers from Oklahoma City Air Logistics Center (OC-ALC) who worked on the LARPS system have been directly involved in every step of the development of the RLCRS design. The primary obstacle identified with the LARPS system was the path programming to guide the water strip head across the aircraft surface. To help overcome this and other related technical challenges, a team of industry leaders in robotic motion controls and systems integration, laser optics, beam delivery systems, lasers, and depainting were assembled to assist with development of the RLCRS.

The RLCRS integrates advanced laser coating removal technology with an automated robotic system. The individual components of the RLCRS include the laser, robotic base, beam delivery system, laser scanner, and waste extraction systems and parts cart. The use of laser paint stripping systems is applicable to depainting activities on large off-aircraft components and weapons systems for the DoD.

In this Environmental Security Technology Certification Program (ESTCP) project, design, assembly, and debugging of this system were performed at Concurrent Technologies Corporation (*CTC*) in Johnstown, PA. Following debugging at *CTC*, a demonstration of this system was performed at the OC-ALC at Tinker AFB, Oklahoma City, OK. The objective of this demonstration was to verify the ability of a RLCRS to meet the requirements for coatings removal in a production environment without causing physical damage to the substrate. A second objective of this demonstration was to validate the pollution reduction that could be achieved through use of laser coating removal systems across the DoD.

The demonstration showed that the RLCRS is feasible for coating removal from large off-aircraft parts, including but not limited to, KC-135 ailerons, rudders, landing gear doors, elevators, and flaps. Almost all wastes associated with the current chemical removal process would be eliminated by the implementation of this technology. The only wastes that remain are the removed coating which is captured in filters, wastewater from rinsing the parts after coating removal, and minor masking materials and personal protective equipment (PPE) (i.e., aluminum tape, cotton gloves, and wipes).

The cost assessment showed that the implementation of the RLCRS results in a labor savings of approximately $7.4 million, an annual materials cost savings of approximately $113,600, and a waste management cost avoidance of approximately $60,000. The total annual operating cost savings equals approximately $7.5 million. A life-cycle cost analysis demonstrated that implementation and use of the RLCRS for coating removal of the targeted KC-135 parts would result in 15-year life-cycle cost savings greater than $111 million. These cost savings translate into a payback period of approximately 0.3 years.

Other Air Force depots and DoD facilities that perform chemical depainting of large off-aircraft parts will also realize similar cost savings. For example, if similar cost savings were assumed at all three of the major Air Force depots that perform chemical depainting operations on aircraft parts, the combined cost estimates would result in labor savings of approximately $66.6 million, an annual materials cost savings of approximately $1 million, and an annual waste management cost avoidance of approximately $540,000. The total annual operating cost avoidance would result in approximately $67 million per year for the U.S. Air Force (USAF).

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

This RLCRS project, led by OC-ALC, and supported by ESTCP, Headquarters Air Force Materiel Command (HQ AFMC) and Air Force Research Laboratory (AFRL), developed, demonstrated, and validated an RLCRS for removal of coatings from large off-aircraft weapon system components.

This project was built on two SERDP projects, PP-139 Laser Cleaning and Coatings Removal and PP-134 LARPS, which were undertaken to automate the coatings removal process. The RLCRS is based on an existing gantry-style robot, but the ultimate goal was not to design a one-of-a-kind system usable on only one specific platform, but rather a system of commercial off-the-shelf (COTS) components that can be easily integrated into other DoD depot operations. This allows individual depots to adapt the technology to meet their specific needs, such as different component configurations or space limitations due to facility size.

Assembly and debugging of this system was performed at *CTC* in Johnstown, PA. Following debugging at *CTC*, the system was installed at OC-ALC. A demonstration of the system was then conducted to validate the operation of the system on actual parts that are typically removed from the aircraft and processed at this depot. These parts included ailerons, landing gear doors, rudders, flaps, and elevators.

2.2 PROCESS DESCRIPTION

2.2.1 Description of Robotic Laser Coating Removal System

The RLCRS is made of several subsystems that are integrated together into an automated system. The individual components include the laser, robotic base, beam delivery system, laser scanner, waste extraction systems, and parts cart. The basic foundation of this system is the laser and the robotic base, which are detailed in the following sections.

2.2.1.1 Laser

Laser is an acronym for light amplification by stimulated emission of radiation. A laser beam is generated by an energy source that excites atoms of a lasing medium to emit photons in an optical resonator. The energy source is typically an electrical discharge, flash lamp, or diode laser. The lasing medium may be a gas, such as carbon dioxide (CO_2) mixed with nitrogen (N_2) and Helium (He); a solid, such as neodymium:yttrium-aluminum garnet (Nd:YAG); or, although not common, a liquid. Stimulated emission occurs as two reflectors in the optical cavity mirror reflect the emitted photons, further exciting other atoms to emit photons with the same wavelength, phase, and direction. The coherent radiation (laser beam) is then discharged through one of the reflectors.

Optical output from a laser may be a continuous wave or pulsed beam, depending on how the reflectors are controlled. Continuous wave lasers reflect photons so that the number of stimulated emissions equals the number of photons in the optical output. These lasers are

efficient in converting electrical energy to coherent radiation and, thus, have widespread industrial use.

In order to select an appropriate laser system that would meet the process requirements of large area coating removal, an independent study was commissioned to determine the specifications required for any laser that would be implemented on the RLCRS. This study was performed by the Fraunhofer Institute and summarized in the report *Evaluation of Laser Gantry* (Heinemann, 2005). The results of this study were evaluated and compiled into a performance-based request for proposal (RFP) that was distributed throughout the laser industry. In response to this RFP, 15 laser systems (nine CO_2, three Nd:YAG, and three diode laser systems) were proposed for use in the RLCRS by 10 laser manufacturers. An intensive technical evaluation was performed of these COTS laser sources considering the laser specifications, maturity of the laser system, and maintenance requirements for the proposed laser system. At the completion of this evaluation a 6 kW CO_2 laser from Rofin-Sinar was selected for use in the RLCRS. This laser provided the highest quality laser beam of any of the lasers that were proposed at a power level that is sufficient to rapidly remove coatings without causing excessive heating of the substrate. A picture of the Rofin-Sinar laser that was selected for use in the RLCRS is provided in Figure 1.

Photos courtesy of Rofin-Sinar

Figure 1. Six kW CO_2 laser system.

2.2.1.2 <u>Robotic Platform</u>

The robotic base of the RLCRS system (Figure 2) is an existing gantry style robot that was designed and manufactured by PaR Systems, Inc. of Shoreview, MN. This robot was originally manufactured in 1997 as part of a SERDP-funded program and was available for this project at no cost. This gantry robot has an operating envelope of approximately 10 ft x 10 ft x 5 ft and is equipped with hollow rotary joints at the rotational axes of the gantry. This allowed for convenient placement of the beam delivery mirrors at these axes points.

Because of the age of this equipment, a full update of its control system was required. For this update, all control hardware was replaced with a modern Giddings and Lewis motion controller, and a new control software program was created.

Figure 2. PaR XR125 Gantry robot.

A non-contact contour following system was also implemented as part of the revised control system. This contour following system allows for the robot to automatically process any part that fits within the operating envelope of the gantry. The system operates by using seven proximity sensors mounted at the workhead to develop a three-dimensional map of the part surface. Any part that is placed in the operating envelope of the gantry robot will be processed using a series of slightly overlapping paths along the length of the part. The robot performs a mapping step as it moves from the front of the part to the rear, then strips that area as it moves from the rear to the front. The next path over is mapped as the robot returns to the rear.

2.2.2 Personnel/Training Requirements

Personnel training requirements are prescribed by the Air Force Occupational Safety and Health (AFOSH) Standard 48-139 and the American National Standards Institute (ANSI) document Z136.1-2007. Laser safety training, given by the base laser safety officer (LSO), is required for all operators of the system. The safety training is required to include information on the potential laser and ancillary hazards and the control measures for the laser equipment that will be used. Topics that are required include:

- Fundamentals of laser operation and nature of laser radiation
- Bio-effects of laser radiation on the eye and skin
- Significance of specular and diffuse reflections
- Non-beam hazards of lasers and ionization radiation hazards
- Laser and laser system classifications, warning signs, and labels
- Engineering and administrative/procedural control measures
- Overall responsibilities of management and employees
- Medical surveillance practices
- Good laser safety practice
- Common causes of accidents
- Emergency procedures in case of an accident.

Laser safety training is required for not only the system operators, but also technicians, engineers, and maintenance personnel who are working with or around the laser. After the initial training, annual refresher training is required.

In addition to the laser safety training, the operators must also be trained on the operation of all the major pieces of equipment, including the laser, scanner, effluent removal system, chiller, and software controls. This training is required only once and was provided by *CTC* and the system integrator when the RLCRS was installed at OC-ALC in December 2007. Any new operators that have not received this initial equipment training will receive on-the-job training by the base process supervisor.

2.2.3 Health and Safety Requirements

The laser system in the RLCRS is a Class 4 laser and requires specific safety requirements as outlined in AFOSH Standard 48-139, ANSI Z136.1-2007 and the Occupational Safety and Health Administration (OSHA) instruction standard PUB 8-1.7.

Personnel who routinely work in the laser environment are required to undergo a medical examination before an initial assignment to laser duties and as soon as practical following termination of duties involving lasers. Periodic examinations are not required under the relevant standards. Medical examinations will involve:

- Ocular history: past ocular history and family history
- Visual acuity: best corrected distant and near vision measured
- Macular function: macular function tested with an Amsler grid
- Color vision: color vision test to document color vision discrimination.

A dedicated facility was identified for the implementation and operation of the RLCRS. This included a fully enclosed, passcode-secure area and a fully enclosed control booth that was constructed beside the gantry robot that includes a large window, manufactured with materials consistent with the requirements for Class 4 CO_2 laser viewing. A further description of the physical setup of the equipment and room is given in Section 3.4.

In accordance with the AFOSH and ANSI standards, wherever possible, engineering controls have been instituted to ensure a safe environment for the system operators. Foremost was the construction of a separate control booth that encloses the operator. The operator is not able to fire the laser beam unless he is operating the system from inside the control room. Additionally, appropriate interlocks are in place to shut down the laser if the door to the enclosure or the control booth is opened during operation. The window of this control booth is constructed of an acrylic material of suitable thickness to provide the required optical density for viewing the laser coating removal process with a 6 kW CO_2 laser.

Also, appropriate engineering controls were instituted into the RLCRS itself. In accordance with ANSI Z136.1-2007 these controls include, but are not limited to:

- Interlocked protective housing for the laser source that prevents any light from leaking out
- Keyed control of the laser source
- A beam stop that prevents the beam from leaving the source without having to shut down the laser
- Fully enclosed beam path with interlocks on each mirror in the system
- Activation warning system that includes an audible siren and a visible light
- Laser emission delay
- Emergency stop or panic buttons at various points in the laser enclosure and in the control booth
- Interlocked doors to the laser enclosure and to the operator control booth.

2.2.4 Ease of Operation

Operation of the RLCRS first requires simple daily inspections of the status of the laser chamber gas, laser chiller fluid level, and scanner chiller fluid level. The laser chamber gas is required to be changed every third day through a simple automated process. After this daily maintenance, the operator can begin use of the system.

Operator involvement is limited compared to the traditional chemical coating removal process. Operating the RLCRS process requires only two operators versus the three operators for chemical stripping process, in accordance with the OSHA requirements for operating robotic processes.

Operators begin by placing the desired part onto the parts cart and moving the parts cart to its starting position. The operators then use the robot pendant to position the robotic end effector slightly in front and above the part at the point where stripping should begin along its width. The operators can then enter the control room and initiate the automated operation of the system.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

In the past decade, laser systems have generated significant interest as cleaning and paint removal tools. The advantages of using lasers for paint removal are that it requires no sample preparation, is non-contact, and uses no secondary medium that increases the amount of material to dispose.

A potential limitation to the technology is the potential for the energy beam to overheat the substrate while performing stripping operations. The controllable nature of the energy beam with the integration of scanning technology addresses this issue. Hence, with the proper parameters, coatings can be selectively removed with minimal influence to the underlying substrate.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The main performance objective of this demonstration was to remove coatings from large off-aircraft parts using the RLCRS without causing damage to the substrate materials. The performance objectives for this demonstration are detailed in Table 1.

Table 1. Performance objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance Metric	Actual Performance (Objective Met?)
Quantitative	Maintain specifications for affected parts/substrates	Pass individual material tests described in the Joint Test Protocol (JTP)	Yes
Qualitative	Coating removal without substrate damage	No visual damage	Yes
Quantitative	Meet or exceed current coating removal process rates	Meet or exceed current coating removal process rates, which include prep time, strip time, and cleanup time	Yes

3.2 SELECTION OF TEST PLATFORM/FACILITY

This demonstration was conducted at OC-ALC, which will serve as the final installation point for this system. Demonstration of the system was performed using large off-aircraft components for the KC-135. These components were selected due to the high volume of parts that are processed, the sizes of the parts, and the willingness of the KC-135 program to participate.

3.3 TEST PLATFORM/FACILITY HISTORY/CHARACTERISTICS

OC-ALC's mission is dedicated to providing worldwide technical logistics support to Air Force weapon systems, as well as associated equipment and commodity items. Its major product line directorates of aircraft, propulsion, and commodities manage, maintain, and procure resources to support first-line overhaul and maintenance of the B-1, B-52, E-3, and KC-135 aircraft, and several missile systems. OC-ALC houses some of the most sophisticated technical repair and manufacturing processes in the world, acquiring and maintaining aviation systems in partnership with customers and suppliers. Other directorates furnish center-wide services such as environmental management, financial management, procurement policy, technical and industrial plant maintenance, and computer services.

The OC-ALC encompasses 138 acres of indoor maintenance facilities and 93 acres of covered warehouse space. Historic Building 3001, headquarters of the OC-ALC, covers 62 acres and stretches for 0.7 mile. Within its walls, workers perform a vast array of maintenance on aircraft, engines, components, and accessories and perform a multitude of necessary administrative tasks.

3.4 PHYSICAL SETUP

The RLCRS was transitioned to and installed at OC-ALC in October and November 2007. Following the system start-up in December 2007, the full ESTCP demonstration was performed on off-aircraft components in March and April 2008. A photo of the RLCRS as it was installed is shown in Figure 3. Initially, the RLCRS was to be housed in the OC-ALC depaint facility in Building 2122. However, because of space availability and timing concerns, the system was installed in Building 3105. This facility provided some advantages in that there was an existing enclosure present in the building that was suitable to house the RLCRS. This enclosure had the required utilities present and was suitably sized to house the RLCRS and to allow for staging of the large off-aircraft components. Additionally, this enclosure was equipped with an overhead gantry suitable for lifting the off-aircraft parts from their trailers and positioning them onto the parts cart.

Figure 3. RLCRS installed at OC-ALC.

The system and all ancillary equipment were installed in a fully enclosed, passcode-secure area within Building 3105. Additionally, a fully enclosed operator booth was constructed beside the gantry robot that included a large window manufactured with materials consistent with the requirements for Class 4 CO_2 laser viewing.

Laser safety precautions were designed and installed in accordance with Air Force standard laser safety requirements (AFOSH 48-10 Laser Radiation Protection Program). Each door to the area was interlocked with operating software that deactivates the laser and robot if a door is opened during stripping operations. Each door was also equipped with the necessary laser safety warning lights, alarms, and clearly posted warning signs.

At the completion of the demonstration the RLCRS system will be put into production usage. Data collection will continue for 1 year as the system is used in the production environment.

3.5 SAMPLING/MONITORING PROCEDURES

Prior to the demonstration at OC-ALC, debugging, optimization, and screening testing of the RLCRS was conducted for nine months at *CTC* in Johnstown, PA. Diagnostic tests of the functionality of the RLCRS were performed to measure the laser beam delivery system stability, beam losses, beam power, and spot size at the work surface; scan speed provided by the scanner; contour follower fidelity; and effluent control air flow rate. Optimization testing was conducted to determine the operating parameters that were used throughout the demonstration. This testing was devoted to optimizing the air flow geometry, laser beam parameters, and scan parameters to achieve good coating removal rates with minimal substrate heating. Specifically, the testing evaluated:

- Laser power (held constant at maximum value for most tests)
- Irradiance spot size (varied by varying the scanner working distance)
- Scan width (held constant at 100 mm for most tests)
- Scan rate (held constant at highest possible rate)
- Laser beam duty cycle (held constant for most tests)
- Robot mast sweep speed
- Robot mast sweep direction relative to air flow direction
- Number of robot arm sweep passes
- Air knife pressure.

Mechanical testing was performed during the debugging, optimization, and screening testing at *CTC* to demonstrate that the use of the RLCRS causes no effect on the part substrate beyond the effects currently encountered using chemical stripping. This testing was conducted using 24-inch x 18-inch test panels constructed of the various substrates and coating systems that are representative of the parts that were targeted for use with RLCRS. Each of these test panels was subjected to four coating and laser stripping cycles. The mechanical test results from the laser stripping of these test panels was compared to the baseline unprocessed "control" panels and to the test panels that had been stripped using the conventional chemical depainting processes. All panel testing was performed in accordance with the JTP (*CCT*, 2006). This JTP details the tests that were performed, the frequency of these tests, and the standard procedures that were followed for each of the tests. This debugging, optimization, and screening testing is described in further detail in the RLCRS Demonstration Plan for Debugging/Optimization (*CCT*, 2007).

The demonstration at OC-ALC tested the ability of the system to effectively strip KC-135 flight control components during the course of routine depot maintenance operations. Five parts were processed during the demonstration—a landing gear door, rudder, outboard flap, elevator, and outboard aileron. All the parts processed during this demonstration were subjected to a visual examination for any existing damage prior to being stripped by the RLCRS. Additionally, the coating thickness and dimensions of every part were measured and recorded. Each part was then stripped using a consistent set of parameters, as detailed in Table 2, which were established during the debugging and optimization testing at *CTC*. The path overlap parameter varied between 0.125 inches to 1 inch, and was based on the part contours; the greater the contour/curve, the more overlap required.

Table 2. Operating parameters.

Units Measured	Value
Laser power (W)	6000
Laser power at surface (W)	4500
Focused spot size (mm^2)	4.4
Irradiance (kW/cm^2)	102.3
Scan rate (m/s)	7
Scan width (mm)	127
Stand-off distance (mm)	500
Sweep rate (in/s)	2.75

This product testing on large off-aircraft parts was conducted in accordance with Section 4.0 of the JTP. The test requirements are detailed in Table 3. The JTP called for substrate temperature to be recorded during demonstration testing, but it was discovered that this was not feasible without modifying the various aircraft parts due to their shape and construction. Because extensive temperature monitoring was performed during the optimization testing, it was decided to omit the temperature evaluation on the actual parts. The test results from the demonstration are provided in the ESTCP Final Report.

Table 3. Test requirements.

Test Name	Acceptance Criteria	Reference	Trials
Strip rate	Meet or exceed current coating removal process rates, which include prep time, strip time, and cleanup time	Not Applicable (N/A)	Every part
Visual assessment	No visual warping, burning, thermal effects or other damage at 10X magnification	N/A	Every part
Substrate temperature	300°F maximum spike temp	N/A	Every part[1]
Coatings removal	Coating material removed completely	N/A	Every part
Strippable area assessment	At least 80% of surface area stripped	N/A	Every part

[1] Unable to perform during demonstration

3.6 ANALYTICAL PROCEDURES

Analytical testing procedures were used for testing the panels and parts stripped during this demonstration. The various standards that were followed during these tests are provided in Table 4.

Two laboratories were utilized in completing the required testing for the demonstration and pre-demonstration testing. *CTC*'s laboratories applied the coatings to each of the test panels and performed the visual examinations, conductivity tests, ultrasonic tests, and hardness measurements. The Laboratory and Material Services departments at *CTC* were chosen because of their location to the RLCRS demonstration site and their capabilities in the coating of test coupons and materials testing.

The AFRL and their support contractor, University of Dayton Research Institute (UDRI), performed all other testing required under the JTP, including tensile, fatigue, peel resistance, and flexural properties testing. This facility was chosen due to the laboratory's well-established record of material testing.

Table 4. Test requirements.

Test Name	Acceptance Criteria	Reference
Screening Testing on Panels		
Aluminum Substrate Assessment		
Strip rate	N/A. Information purposes only	N/A
Visual assessment	No visual warping, burning, thermal effects, or other damage at 10X magnification	N/A
Substrate temperature	300°F maximum spike temp	N/A
Superficial rockwell hardness	Compare with control sample	ASTM E18
Electrical conductivity	Compare with control sample	MIL-STD-1537
Tensile testing	Compare with control sample	ASTM E8
Fatigue testing	Compare with control sample	ASTM E466
Honeycomb Structural Materials Assessment		
Strip rate	N/A. Information purposes only	N/A
Visual assessment	No visual warping, burning, thermal effects, or other damage at 10X magnification	N/A
Ultrasonic inspection of honeycomb materials	Compare with control sample	ASTM E114
Peel resistance	Compare with control sample	ASTM D1781
Flexural properties	Compare with control sample	MIL-STD-401
Demonstration Testing on Parts		
Coating strip rate	N/A. Information purposes only	N/A
Visual assessment	No visual warping, burning, thermal effects, or other damage at 10X magnification	N/A
Substrate temperature	300°F maximum spike temp (metallic) 200°F maximum spike temp (composite)	SAE MA4872

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4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

All performance data may be found in the ESTCP Final Report. Table 5 summarizes the results of the screening testing performed to determine the effects of laser stripping on part substrates. Table 6 summarizes the results of the demonstration testing performed on actual aircraft parts.

Table 5. Screening test results.

Performance Criteria	Baseline	Baseline Baked	Laser Stripped	Chemically Stripped	Acceptance Criteria
Coating Strip Rate (ft^2/min)					
2024 Al – Bare	N/A	N/A	1.0	N/A	Information purposes only
2024 Al - Clad	N/A	N/A	1.0	N/A	
2024 Al – Anodized	N/A	N/A	0.8	N/A	
7075 Al – Bare	N/A	N/A	1.0	N/A	
Aluminum honeycomb 0.010-inch face sheet	N/A	N/A	0.9	N/A	
Aluminum honeycomb 0.016-inch face sheet	N/A	N/A	0.9	N/A	
Visual Damage Assessment					
2024 Al – Bare	No surface abnormalities	No surface abnormalities	No surface abnormalities	No surface abnormalities	No visual warping, burning, thermal effects, or other damage at 10X magnification
2024 Al - Clad	No surface abnormalities	N/A	No surface abnormalities	N/A	
2024 Al – Anodized	No surface abnormalities	N/A	Warping, burning of anodize layer	N/A	
7075 Al – Bare	No surface abnormalities	No surface abnormalities	No surface abnormalities	No surface abnormalities	
Aluminum honeycomb 0.010-inch face sheet	No surface abnormalities	No surface abnormalities	No surface abnormalities	No surface abnormalities	
Aluminum honeycomb 0.016-inch face sheet	No surface abnormalities	No surface abnormalities	No surface abnormalities	No surface abnormalities	
Substrate Temperature (°F)					
2024 Al – Bare	N/A	N/A	271° F	N/A	300°F max for aluminum 180°F max for honeycomb
2024 Al - Clad	N/A	N/A	287° F	N/A	
2024 Al – Anodized	N/A	N/A	248° F	N/A	
7075 Al – Bare	N/A	N/A	261° F	N/A	
Aluminum honeycomb 0.010-inch face sheet	N/A	N/A	161° F	N/A	
Aluminum honeycomb 0.016-inch face sheet	N/A	N/A	160° F	N/A	

Table 5. Screening test results. (continued)

Performance Criteria	Baseline	Baseline Baked	Laser Stripped	Chemically Stripped	Acceptance Criteria
Superficial Hardness (HR15T)					
2024 Al – Bare	83.0	83.4	82.9	82.8	Compare with baseline sample
7075 Al - Bare	88.4	88.8	88.7	89.0	
Electrical Conductivity (%IAC)					
2024 Al – Bare	30.2	30.1	30.1	30.0	Compare with baseline sample
7075 Al - Bare	32.0	32.2	32.1	32.2	
Tensile Properties					
Yield Strength (ksi*)					Compare with baseline sample
2024 Al – Bare	53.1	52.7	52.7	52.5	
7075 Al - Bare	75.0	75.7	76.0	75.6	
Tensile Strength (ksi)					
2024 Al – Bare	71.4	71.5	71.6	71.3	
7075 Al - Bare	84.7	85.0	84.9	85.0	
Elongation (%)					
2024 Al – Bare	16.4	17.0	16.9	17.1	
7075 Al - Bare	13.7	12.7	12.9	13.2	
Fatigue Properties					
Average Cyclic Life (cycles) – Max Stress 45 ksi					Compare with baseline sample
2024 Al – Bare	312,743	192,281	166,619	184,578	
7075 Al - Bare	93,904	118,372	133,809	64,732	
Average Cyclic Life (cycles) – Max Stress 55 ksi					
2024 Al – Bare	40,562	52,628	40,305	57,941	
7075 Al - Bare	36,764	22,776	32,421	31,320	
Ultrasonic Inspection					
Aluminum honeycomb 0.010-inch face sheet	No discontinuity	No discontinuity	No discontinuity	No discontinuity	No discontinuity
Aluminum honeycomb 0.016-inch face sheet	No discontinuity	No discontinuity	No discontinuity	No discontinuity	
Peel Resistance (Average Peel Torque (in-lb$_f$/in))**					
Aluminum honeycomb 0.010-inch face sheet	23.5	22.8	23.2	25.6	Compare with baseline sample
Aluminum honeycomb 0.016-inch face sheet	27.9	19.9	27.2	26.1	
Flexural Testing (Average Peak Flexural Load (lb$_f$))**					
Aluminum honeycomb 0.010-inch face sheet	950	1172	1267	986	Compare with baseline sample
Aluminum honeycomb 0.016-inch face sheet	1447	1557	1202	1436	

*ksi = kips per square inch

*AFRL/Materials Integrity Branch (RXSA) determined that the panels as manufactured are not representative of structural materials used on flight controls; therefore, no valid conclusions can be drawn from this data set. Peel resistance testing will be redone using new honeycomb structural materials.

Table 6. Demonstration test results.

Performance Criteria	Laser Strip				
	Landing Gear Door	Rudder	Outboard Flap	Elevator	Outboard Aileron
Coating strip rate (ft^2/min)	1.53 (~2.6 mil)	1.12 (~6.1 mil)	1.86 (~3.4 mil)	1.86 (~3.6 mil)	2.03 (~3.4 mil)
Coating strip rate per mil coating removed (ft^2*mil/min)	3.97	6.81	6.33	6.79	7.41
Visual (warping/denting)	No	No*	No	No	No
Maximum substrate temperatures (°F)	Not recorded	Not recorded	Not recorded	Not recorded	Not recorded

* The rudder had one section of the part that was a magnesium substrate. This substrate was not one of the substrates that had been identified for this project; therefore, no optimized laser parameters had been developed for safe processing on magnesium. As a result, the magnesium panel did incur warping. Because there is currently no laser operating parameters for magnesium substrates that will not damage the substrate, a procedure for operators to check for the presence of magnesium prior to processing a part has been established.

4.2 PERFORMANCE CRITERIA

The demonstration at OC-ALC was evaluated based on the results of the panel and parts testing and summarized in Table 7.

Table 7. Expected performance and performance confirmation methods.

Performance Criteria	Expected Performance Metric (pre-demonstration)	Performance Confirmation Method	Actual Performance (post demonstration)
PRIMARY CRITERIA			
Visual assessment	No visual warping, burning, thermal effects, or other damage at 10X magnification	N/A	No visual warping, burning, thermal effects or other damage on aluminum substrates Some burning on magnesium panel that was encountered
Substrate temperature	300° F peak temperature for aluminum parts	N/A	Temperatures less than 287º F documented in pre-demonstration testing
Strippable area assessment	At least 80% of surface area stripped	N/A	Landing gear door: 100% Rudder: 82% Elevator: 82% Outboard aileron: 73% Outboard flap: 49%
Total process time	Total process times to strip components less than current times	Record Keeping	Total process times are less than current times
Hazardous materials	Reduce the use of chemical strippers by 90% Generate no new hazardous materials	Record keeping	No chemical strippers used

Table 7. Expected performance and performance confirmation methods. (continued)

Performance Criteria	Expected Performance Metric (pre-demonstration)	Performance Confirmation Method	Actual Performance (post demonstration)
Process waste	No new process waste generated	Record keeping	No new waste stream generated
SECONDARY CRITERIA			
Reliability	No breakdowns	Record keeping	No breakdowns
Ease of use	Can operate with two people	Operating experience	System is operated by two people
Versatility	Capable of intermittent and long-term operation Capable of de-coating components other than the chosen candidate parts	Operating experience	System is capable of intermittent and long-term operation System is capable of use on any part that fits within operating envelope of the system
Maintenance	Regular change of vacuum filters Annual laser preventative maintenance	Operating experience	No maintenance has been required to date
Scale-up constraints	N/A	N/A	N/A

4.3 DATA EVALUATION

This testing was conducted to validate the RLCRS for use in coatings removal operations on large components that are removed from aircraft during depot maintenance. This technology would reduce or eliminate DoD dependence on the hazardous chemicals and processes that are currently used to remove coatings.

The objective of the screening testing was to verify the ability of the RLCRS to effectively remove select DoD coating systems without causing physical damage to the substrate. Screening test results indicated that use of the RLCRS has no detrimental effect on 2024 and 7075 aluminum substrates. All testing performed on these substrates, including superficial hardness, conductivity, tensile testing, and fatigue life, showed no degradation in material properties from baseline conditions.

The screening test results show that use of the RLCRS on honeycomb structures causes no detectible defects when visually examined and subjected to ultrasonic inspection. Additionally, the testing showed that the backside of the honeycomb face sheet will not be exposed to temperatures greater than 161°F during processing when the RLCRS is operated at a robotic sweep speed of 3.75 inch/sec. Due to defects in the manufacturing of the honeycomb structural test materials, comparisons in the effects of the RLCRS on peel resistance and flexural properties cannot be made. It is recommended that additional honeycomb structural test materials be procured and this testing be repeated.

The objective of the demonstration testing was to verify the ability of the RLCRS to effectively process the parts that are encountered during depot maintenance operations. Results from the demonstration testing show that the RLCRS can effectively process a wide variety of parts that

are encountered at OC-ALC. The RLCRS system was able to efficiently remove coatings from all of the condemned parts that were processed without causing damage.

4.4 TECHNOLOGY COMPARISON

The key area of comparison between the existing chemical coating removal process and the RLCRS is the total time required to strip a part.

For the chemical stripping process, the total process time is relatively long because it requires long dwell times for the chemicals to work. Because these chemicals are sprayed on and allowed to dwell for a specified period of time the overall processing time is relatively independent of the part size. Typically, after the bulk chemical stripping several additional applications to specific areas are required to "nitpick" areas that were not stripped during the bulk stripping. Overall, the chemical stripping process can take up to 2 full flow days to process the parts that are targeted for the RLCRS.

For the laser stripping process, there are areas of the parts that were not stripped with the RLCRS. These areas will be stripped using the handheld laser systems that OC-ALC had previously qualified for use on KC-135, E-3, and B-52 component parts.

In order to perform a comparison of the total process time associated with the chemical stripping process and the RLCRS process, it was necessary to develop an estimate of the time required to use a handheld laser to strip the areas that were not accessible to the RLCRS. This estimate was developed by the manufacturer of the handheld laser system, Clean-Lasersysteme. Representatives from Clean-Lasersysteme attended the demonstration testing and reviewed the areas that would require handheld stripping. They then developed estimates based on an average coating thickness of 5 mil, measurements of the areas requiring handheld processing, and the normal removal rates that OC-ALC achieves using their systems. This information is compiled into a comparison of the process times in Table 8.

Table 8. Total process time comparison.

	Actual RLCRS Process Time (hr)	Estimated Handheld Laser Process Time (hr)	Total Process Time of Alternative (hr)	Current Process Time (hr)
KC-135 Landing gear door	1.6	6	7.6	24
KC-135 Rudder	6.5	6	12.5	48
KC-135 Elevator	2.9	6	8.9	48
KC-135 Outboard aileron	2	6	8	24
KC-135 Outboard flap	2.3	9	11.3	24

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5.0 COST ASSESSMENT

5.1 COST REPORTING

The primary objective of the cost assessment is to determine whether RLCRS can be implemented with an acceptable payback period. An economic analysis was conducted using the Environmental Cost Analysis Methodology (ECAM^{SM}) (NDCEE, 1999) cost estimating tool, comparing the current chemical depainting process of KC-135 off-aircraft parts that is performed at OC-ALC (Baseline Scenario) to the purchase and installation of an RLCRS (Alternative Scenario). Information regarding the costs associated with the current chemical stripping operations at OC-ALC was obtained through a standard questionnaire and gathered during a site visit. This information was then entered into the Environmental Protection Agency's (USEPA) pollution prevention cost accounting software, P2 Finance (P2 Finance, 1996) according to ECAM. This software performs the calculations for payback period, net present value (NPV), and internal rate of return (IRR).

For this cost assessment, the candidate RLCRS was assumed to replace the current chemical stripping process for the selected KC-135 off-aircraft parts (ailerons, rudder, flaps, elevators, and landing gear doors) that is performed at OC-ALC. Since the RLCRS is unable to strip the bracket areas and extreme curvatures of the parts, it was assumed that a portable handheld laser system would perform the coating removal of these areas.

The chemical stripping of the selected parts was targeted as the initial process for implementation of the laser system; however, the candidate laser systems can potentially be utilized on many more applications throughout the depots. For example, the RLCRS may replace chemical stripping, media blasting, and hand sanding applications on other large off-aircraft parts from other airframes such as the B-52, E-3, and B-1.

The following general assumptions were made to complete the cost analysis shown in Table 9. All calculations and assumptions are available in Appendix B of this report.

- A rate of $236 per hour was assumed for all types of labor, regardless of geographic location or specific skill requirements. This is a fully burdened rate that was provided by HQ AFMC.
- Baseline chemical stripping requires three people per shift, three shifts per day. This is based on information provided by OC-ALC personnel.
- RLCRS would require two operators per shift for three shifts per day.
- Environmental Health and Safety (EHS) costs (permitting and reporting) for RLCRS would be the same as the current process; therefore, EHS issues were not factored into the cost analysis.
- Nitpicking step would be performed using a portable handheld laser system.
- Capital costs of the portable handheld system would not be considered with the RLCRS capital costs since OC-ALC currently has a portable laser system.

Table 9. Cost analysis for Baseline and Alternative Scenarios.

Category	Input Parameter	Baseline Scenario Current Chemical Strip	Alternative Scenario RLCRS
Direct Environmental Process Costs			
Start-up costs (one-time fees)	Equipment cost	$0	$819,982
	Installation cost	$0	$79,384
	One-time engineering cost[1]	$0	$1,027,471
	Training of operators	$0	$5660
	Total Capital/Start-Up Costs	**$0**	**$1,932,497**
Labor	Labor to strip parts	$9,558,000	$2,152,000
	Lost labor for maintenance downtime	$2260	$28,300
	Total Annual Labor Costs	**$9,560,260**	**$2,180,300**
Materials	Chemicals	$77,000	$0
	Alkaline soap	$5000	$0
	PPE	$30,000	$410
	Masking materials	$2000	$84
	Equipment maintenance consumables	$0	$19,916
	Total Annual Material Costs	**$114,000**	**$20,410**
Utilities[2]	Rinse water	$4300	$0
	Electricity for equipment	$0	$2500
	Total Annual Utility Costs	**$4300**	**$2500**
Waste	Waste rinse water	$20,250	$0
	Trench cleanout by contractor	$32,000	$0
	Filters	$1760	$22
	Paint chips in water	$3440	$0
	Paint chips from stripper	$520	$0
	Contaminated rags & debris	$2150	$108
	Total Annual Waste Costs	**$60,120**	**$130**
Indirect Environmental Costs			
EHS/waste	Reporting requirements, documentation maintenance, etc.	Will not change	Will not change
	OSHA/EHS training[3]	$0	$1180
	Medical exams (Eyes)[4]	$0	$1180 (one-time)
	Set-up waste streams[5]	$0	$940 (one-time)
	Adjusted environmental compliance recurring cost	$8000	$2,200
	Annual Indirect Costs	**$8000**	**$3380 ($5500 first year)**

[1] This is the engineering cost for this demonstration only. A subsequent system is expected to require half the engineering time, which equals a cost of approximately $510,000.
[2] Facility utilities (i.e., lighting, heating, etc.) will not change with the installation of the RLCRS.
[3] Other annual training is required (i.e., safety training, hazardous waste training, etc.) and would not change with the new process. Annual laser training is required for Alternative Scenario.
[4] Medical examinations are required before an individual's initial assignment to laser duties and as soon as practical following termination of duties involving lasers. Periodic examinations are not required under the relevant standards. The exam takes a half hour to complete for each person.
[5] The waste streams for the new system must be set up. This is a one-time event. This setup took 4 hours for one person.

As shown in Table 9, the implementation of the RLCRS results in a labor savings of approximately $7.4 million, an annual materials cost savings of approximately $113,600, and a waste management cost avoidance of approximately $60,000. The total annual operating cost savings equals approximately $7.5 million.

It is estimated that other Air Force and DoD depot facilities that perform chemical depainting of large off-aircraft parts will also realize similar cost savings. For example, if similar cost savings were assumed at all three major Air Force depots that perform chemical depainting operations on aircraft parts, the combined cost estimates would result in labor savings of approximately $66.6 million, an annual materials cost savings of approximately $1 million, a waste management cost avoidance of approximately $540,000, and a total annual cost avoidance of approximately $67 million in cost savings. In addition to cost savings, implementation of the RLCRS will reduce the use of hazardous chemical strippers, hence reduce worker exposure to hazardous chemicals and/or substances.

5.2 COST ANALYSIS

A life-cycle cost analysis was performed using the data from Table 9 to evaluate the decision of whether an RLCRS is a viable alternative to current chemical stripping process for large off-aircraft components. Per ECAM guidance, this approach:

- Estimates the annual cash flows using the cost data described above
- Discounts future cash flows
- Calculates financial performance measures such as NPV and IRR
- Compares these measures with acceptance criteria.

This evaluation began by determining the life-cycle cost associated with implementation of the RLCRS at OC-ALC. This was calculated by totaling the initial investment required as well as the operating, maintenance, and repair costs expected over the 15-year life of the equipment. A summary of the life-cycle cost and life-cycle cost savings associated with the RLCRS is provided in Table 10.

Table 10. Life-cycle cost analysis.

Technology	Installation Cost	Annual Cost	Life-Cycle Cost	Life-Cycle Cost Savings
Chemical stripping	$0	$9,746,680	$146,200,200	--
RLCRS	$1,932,497	$2,206,720	$35,033,297	$111,166,903

Three performance measures for investment opportunities were then considered in the ECAM evaluation: payback period, NPV, and IRR. The payback period is the time period required to recover all the capital investment with future cost avoidance. NPV takes this investment-return analysis one step further by calculating the difference between capital investments and the present value of future annual cost benefits associated with the alternatives. This value represents the life-cycle costs associated with each of the alternatives. The IRR is the discount rate at which NPV is equal to zero.

NPV and IRR account for the time value of money and discount the future capital investments or annual cost benefits to the current year. For this analysis, a study period of 15 years was chosen, and a discount rate of 2.7% was used. This discount rate is based on guidance offered by the Office of Management and Budget (OMB) in Circular A-94, Appendix C (OMB, 2008). It should be noted that OMB provides both *real* and *nominal* rates. *Real* interest rates were chosen and extrapolated for a 15-year life-cycle lifetime. Table 11 shows the calculated 15-year NPV, IRR, and discounted payback period for the RLCRS system.

Table 11. ECAM economic analysis results.

	15 Years
NPV savings	$90,000,000
IRR	390%
Discounted payback period	0.3 years

Table 12 summarizes the investment criteria used to compare the capital costs of the proposed RLCRS to the estimated discounted future savings resulting from its replacement of existing coating removal processes.

Table 12. Summary of investment criteria.

Criteria	Recommendations/Conclusions
NPV > 0	Investment return acceptable
NPV < 0	Investment return not acceptable
Highest NPV	Maximum value to the facility
IRR > discount rate	Project return acceptable
IRR < discount rate	Project return not acceptable
Shortest payback period	Fastest investment recovery and lowest risk

Adapted from *ECAM Handbook* (NDCEE, 1999).

Comparing the investment criteria in Table 12 to the economic analysis results in Table 11 shows that the NPV is positive, the IRR is higher than the 2.7% real discount rate that was used for the financial evaluation, and the discounted payback period of 0.3 years is extremely short. All these factors indicate that the investment is acceptable, is low risk, and will provide a fast investment recovery. These results support the decision to implement the RLCRS process.

The major cost drivers that promote the implementation of the RLCRS process include reduced operational labor costs, direct material costs, and waste disposal costs.

5.2.1 Sensitivity Analysis

A sensitivity analysis was performed to investigate realistic scenarios that reveal the sensitivity of the total costs to the major cost drivers, which include operational labor, direct materials, and waste disposal.

The first cost driver investigated was the operational labor. Concerning the baseline process, the number of operators associated with the stripping of the target components was based on percentages provided by OC-ALC. The number of operators could realistically vary between

two to four people per shift. This would result in labor costs between $6.4 million to $12.7 million per year and a payback period between 0.45 to 0.19 years. When investigating the operational labor for the alternative process, the least accurate piece was the handheld laser coating removal stripping time, which was based on a 5-mil coating thickness and time estimates and calculations performed by the laser manufacturer. The coating thickness could realistically vary between 3 mil to 10 mil for the candidate parts. This would result in labor times for the nitpicking process to vary between 1397 hours to 4657 hours, which would result in total labor costs for the alternative process to be between $1.93 million to $2.7 million per year and a payback period of 0.26 to 0.28 years. Overall, the sensitivity of the operational labor on the payback period is not that significant since the payback period for the worst case scenario associated with the operational labor costs would still be less than a year.

The second cost driver investigated was the combination of direct material and waste disposal costs. These two factors are directly proportional (i.e., when material usage increases, the waste disposal associated with those materials also increases and vice versa) and, therefore, must be considered together. For the baseline process, because the information provided and/or calculated was based in part on percentages, the direct material costs could realistically vary between $75,000 and $140,000, and waste disposal costs could vary between $35,000 and $80,000 per year. This would result in a payback period range of 0.26 to 0.27 years, which shows that these cost drivers are not very sensitive. For the alternative process, the least accurate variable is the waste disposal since the waste disposal sites have not yet been set up by OC-ALC. These costs could realistically range between $100 to $1000 per year. This would result in no variance in payback period, therefore showing that the total costs are not sensitive to this cost driver.

Overall, the sensitivity analysis shows that there is little to no change in payback period with respect to the cost drivers investigated. The one aspect that has the ability to really affect the total costs and financial analysis is the labor dollar rate. The value provided was $236 per hour; however, if this value changed, it would change the payback period. For example, any dollar amount over $236 per hour would positively impact the cost benefit of implementing the RLCRS. Any dollar amount under $236 per hours would start negatively impacting the cost benefit of implementing the RLCRS. At a $50 per hour labor rate, the cost benefit would still be in favor of implementing the RLCRS with an NPV of $18.8 million, an IRR of 88%, and a payback period of 2.5 years.

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6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

The cost of the RLCRS to include the laser and all ancillary equipment (i.e., scanner, chiller, effluent removal system, etc.), installation, training, and engineering costs is approximately $1.9 million. The one-time engineering cost for this demonstration was approximately $1.03 million. However, subsequent systems are expected to require only half of that original engineering cost, which would bring the cost of the whole package down to about $1.4 million if implemented at another DoD facility to replace chemical stripping.

6.2 PERFORMANCE OBSERVATIONS

Testing confirmed the ability of the RLCRS to provide efficient, nonhazardous coating removal. The system provides a reliable, environmentally friendly alternative to the current chemical, blast media, and/or hand sanding coating removal methods. The use of this system requires very minor setup or preparation time (i.e., 15 minutes or less) prior to coating removal operations on a part.

The condemned parts that were processed for this demonstration were coated with severely aged and weathered coatings and heavily covered with dirt and grease. No cleaning or removal of surface contaminants was performed prior to laser processing. The stripped surfaces were completely free from coating and showed no visual indications of damage as shown in Figure 4.

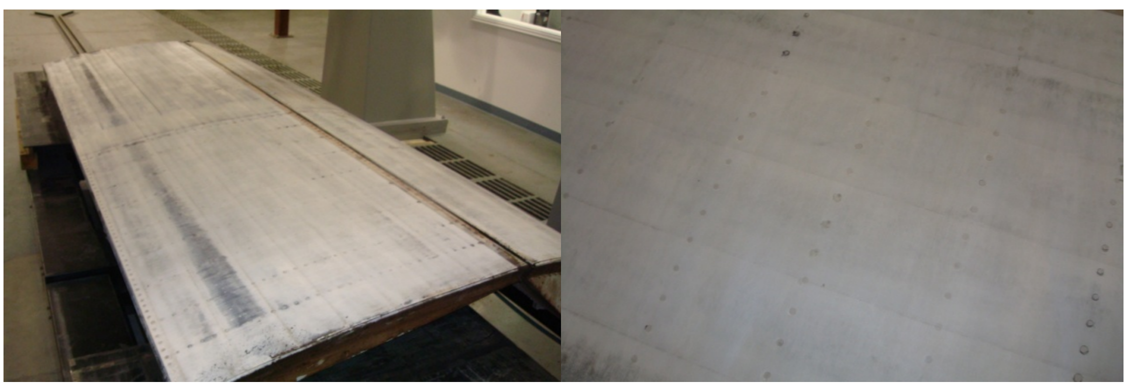

Figure 4. Laser stripped part.

6.3 SCALE-UP

The demonstrations were conducted on full-scale systems; therefore, no scale-up, performance related issues exist. If another depot facility would like to install an RLCRS for similar applications, we recommend that they use a state-of-the-art robotic laser arm instead of a gantry type robot. The gantry style robot imposes some geometric limitations that could be overcome through the use of a robotic arm.

6.4 LESSONS LEARNED

Valuable information was noted during the demonstration of the RLCRS. Lessons learned, which would help a facility with evaluation and implementation of the RLCRS, are listed below:

- This program involved the Occupational, Health, and Safety officers throughout the process of implementation and use of laser coatings removal equipment. The involvement of these individuals from the beginning of the program was highly beneficial and allowed for program buy-in from the Safety Office and a smooth implementation and start-up of the equipment. Involving these individuals is highly recommended for future demonstration and implementation of lasers.
- Clearly defining the substrates that will be encountered at the beginning of the project is important. In the case of RLCRS, if the magnesium substrate had been identified earlier, process parameters could have been developed that would allow for effective operation on this substrate.

6.5 END-USER/ORIGINAL EQUIPMENT MANUFACTURER (OEM) ISSUES

A critical aspect associated with the validation and implementation of the RLCRS technology to replace chemical stripping is the involvement of the stakeholder community throughout the project. To emulate the success of the previous Portable Handheld Laser Small Area Supplemental Coating Removal System (PLCRS) program, which demonstrated handheld laser coating removal for small areas, the relevant stakeholders for this task had already been identified and involved throughout this effort, including the development of the JTP and other requirements for qualification. The stakeholders for this task are listed in Table 13.

Table 13. Demonstration stakeholders.

U.S. Air Force	William Cain	OC-ALC
	Randel Bowman	OC-ALC
	Debora Naguy	AFMC*/A4B
	Tom Naguy	AFRL/Acquisition System Support Branch (RXSC)
U.S. Navy	Kyle Russel	NAVAIR**
	Brad Youngers	NADEP JAX

*Air Force Material Command
**Naval Air Systems Command

The issues that were relevant to the depots and OEMs in addition to the acceptance criteria established in the JTP are the same performance criteria listed in Table 7 of this report. A successful debugging/optimization of the RLCRS technology at *CTC* laid the foundation for a successful demonstration of the technology at OC-ALC and for acceptance of the technology by the Weapon System Program Offices.

6.6 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

No new or additional permits are required for the RLCRS.

7.0 REFERENCES

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APPENDIX A

POINTS OF CONTACT

Point of Contact	Organization	Phone E-Mail	Role
Randel Bowman	OC-ALC	405-736-2736 Randel.bowman@tinker.af.mil	Principal Investigator
Timothy Hoehman	Tinker AFB	Timothy.hoehman@tinker.af.mil	Co-Principal Investigator
Randall Straw	AFRL	937-255-5598 randall.straw@wpafb.af.mil	AFRL Program Manager (*CTC*)
James Arthur	CTC	412-992-5362 arthurj@ctc.com	*CTC* Program Manager

APPENDIX B

DATA AND ASSUMPTIONS

1.0 DATA AND ASSUMPTIONS

For this analysis, it is assumed that the RLCRS system will replace the current chemical stripping process that is performed for large off-aircraft components of the KC-135. The identified components include elevators, main landing gear doors, flaps, rudders, and ailerons. The chemical stripping of the candidate KC-135 components were targeted as the initial process for implementation of the RLCRS, but the system can potentially be utilized on many more applications throughout the depots. For example, the RLCRS system may be used on all types of large off-aircraft components from all different types of aircraft.

1.1 BASELINE DATA AND ASSUMPTIONS

Based on the feedback received from OC-ALC personnel, the approximate annual usage quantities and costs for the baseline chemical stripping operation for the KC-135 candidate parts are provided in Table B-1.

Table B-1. Process usage and costs for Baseline Scenario.

Labor	Number of People (3 shifts)	Total Time (hrs/yr)	Unit Cost	Annual Cost
Labor hours	9	4500	$236.00	$9,558,000
Maintenance downtime	3	3.2	$236.00	$2266
Materials	**Annual Usage**	**Unit**	**Unit Cost**	**Annual Cost**
Chemicals	4400	gal	$17.50	$77,000
Alkaline soap	1100	gal	$4.50	$4950
Safety glasses	36	pairs	$2.50	$90
Neoprene gloves	1125	pairs	$0.79	$889
Face shield	450	shields	$23.16	$10,422
Rubber apron	36	aprons	$17.50	$630
Rubber boots	36	pairs	$62.75	$2259
Chemical shroud	750	shrouds	$17.53	$13,148
Sleeves to cover arms	450	covers	$2.00	$900
Wet suit	9	pairs	$62.45	$562
Fresh air-fed hood	9	hoods	$46.31	$417
Cotton gloves	450	gloves	$0.99	$446
Barrier paper	5	rolls	$178.37	$892
12-inch plastic	5	rolls	$47.38	$237
16-inch plastic	5	rolls	$55.74	$279
1-inch tape	14	rolls	$13.69	$192
2-inch tape	10	rolls	$27.92	$279
3-inch tape	5	rolls	$41.06	$205
Utilities	**Annual Usage**	**Unit**	**Unit Cost**	**Annual Cost**
Rinse water	2,700,000	gal	$0.0016	$4300

Table B-1. Process usage and costs for Baseline Scenario. (continued)

Waste Management	Annual Disposal Amounts	Unit	Unit Cost	Annual Cost
Rinse wastewater	2,700,000	gal	$0.0075	$20,250
Trench cleaning[1]	--	--	--	$32,000
Filters	2000	lb	$0.88	$1760
Paint chips in water	8000	lb	$0.43	$3440
Paint chips from stripper	2000	lb	$0.26	$520
Contaminated rags and debris	5000	lb	$0.43	$2150
Compliance				**Annual Cost**
Adjusted Environmental Compliance				$8000
			TOTAL	**~$9,746,477**

[1] Refer to Section 1.1.5 for calculations of trench cleaning.

1.1.1 Annual Number of Parts De-Painted

OC-ALC processes an average of 52 KC-135 aircraft annually, each with 13 candidate parts identified for stripping with the RLCRS─1 rudder, 4 ailerons, 4 flaps, 2 elevators, and 2 main landing gear doors. Therefore, the annual number of candidate KC-135 parts processed annually was calculated to be 676 (52 x 13 = 676).

OC-ALC personnel stated that the KC-135 parts accounted for approximately 80% of all off-aircraft parts processed at OC-ALC approximately 25% of which are the targeted parts for RLCRS. Therefore, the candidate parts account for 20% (0.80 x 0.25 = 0.20, or 20%) of the total parts chemically de-painted at OC-ALC. This percentage was used to calculate other usage amounts.

1.1.2 Annual Labor Requirements

Paint stripping of the identified component parts is performed in two facilities at OC-ALC: Building 2122 and Building 3228. OC-ALC personnel provided a breakdown of the work performed in these locations that was specific to the parts that will be processed by the RLCRS. The off-aircraft paint stripping workload in these buildings consists of 12 people per shift, 3 shifts per day. As noted in Section 1.1.1, the stripping of the KC-135 candidate parts accounts for 20% of the off-aircraft parts workload. Therefore, the labor requirements for stripping the KC-135 candidate parts calculate to be 3 people per shift (12 x 0.20 = ~2.5, rounded to the nearest whole).

The total time to de-paint the targeted off-aircraft parts was provided by OC-ALC as approximately 4500 hours per year for the 52 KC-135 planes that are processed annually. The loaded hourly labor rates, as provided by USAF representatives, was estimated to be $236 per hour.

Maintenance downtime occurs when OC-ALC has a contractor clean the trenches in Building 2122. Because the cleaning takes 4 hours, there is a loss of 4 labor hours per month, or 48 hours

per year. However, that accounts for chemical stripping of aircraft and off-aircraft parts. Stripping of off-aircraft parts, as provided by OC-ALC, consists of 33% of the total workload. The stripping of KC-135 candidate parts consists of 20% (as mentioned in Section 1.1.1) of the total off-aircraft workload. Therefore, the lost labor time associated with the candidate parts calculates out to be 3.2 hours per year (48 hrs/yr x 0.33 x 0.20 = 3.17 hrs/yr). At an assumed hourly rate of $236, the total cost of lost labor is $2260 (3.2 hrs/yr x 3 people x $236 ≅ $2266).

1.1.3 Annual Material Usage

Chemicals and Soap

OC-ALC provided the total chemical usage for the coating removal in Buildings 2122 and 3228 for FY 2004 (see Table B-1). The FY 2004 total chemical usage (excluding phenol stripper) for small parts was 19,815 gallons. It was assumed that there was a 10% increase in usage from 2004 to 2008 because the number of KC-135 planes processed increased 10% from 2004 to 2008. Therefore, the total chemical usage was calculated to be approximately 59,000 gallons (53,694.2 gal x 1.10 ≅ 59,063 gal), and the total chemical usage for small parts was calculated to be approximately 22,000 gallons (19,815 gallons x 1.10 ≅ 21,797 gallons). Per OC-ALC personnel and noted in Section 1.1.1, the stripping of the KC-135 candidate parts accounts for 20% of the part stripping chemicals used in Buildings 2122 and 3228. Therefore, the annual chemical usage for the candidate parts was calculated to be 4400 gallons (22,000 x 0.20 = 4400). OC-ALC provided bulk cost for the chemical strippers as $17.50 per gallon. The total cost for the targeted parts is calculated to be $77,000 (4400 x $17.50 = $77,000).

Alkaline soap is used to wash the parts prior to stripping. OC-ALC personnel provided the usage as approximately 55 gallons per week for all off-aircraft parts for Building 2122 at a unit cost of $4.50 per gallon. It was assumed that Building 3228 used the same amount of soap. Therefore, the total usage of the soap for the targeted parts was calculated to be 1100 gallons per year (55 gal/wk x 50 wks/yr x 2 buildings x 0.20 = 1100 gal/yr) at a cost of $4,950 per year (1100 gal/yr x $4.50/gal = $4950/yr).

Personal Protective Equipment (PPE)

OC-ALC personnel provided a list of the PPE required to perform the baseline process, as well as the unit cost and replacement time of the PPE on a per person basis. When calculating the total PPE usage per year, the per-person annual usage was multiplied by nine people (three people per shift x three shifts per day). Table B-2 outlines the annual usage and costs for the PPE.

Table B-2. Annual usage and costs of PPE for baseline process.

PPE	Replacement Time	Annual Usage (#/yr/person)	Total Annual Usage	Unit Cost	Total Annual Cost
Safety glasses	1 per 3 mo	4	36	$2.50	$90
Neoprene gloves	1 per 2-3 days	125	1125	$0.79	$889
Face shield	1 per week	50	450	$23.16	$10,422
Rubber apron	1 per 3 mo	4	36	$17.50	$630
Rubber boots	1 per 3 mo	4	36	$62.75	$2259
Chemical shroud	1 per 3-4 days	83	750	$17.53	$13,148
Sleeves	1 per week	50	450	$2.00	$900
Wet suit	1 per year	1	9	$62.45	$562
Fresh air hood	1 per person	1	9	$46.31	$417
Cotton gloves	1 per week	50	450	$0.99	$446
				Total	**$29,763**

Masking Materials

OC-ALC personnel provided the usage and unit cost of the masking materials used for the off-aircraft parts in Building 3228, and it was assumed that the activities conducted in Building 2122 would require approximately the same amount of materials. Based on the percentage of off-aircraft parts that are candidates for the RLCRS, described in Section 1.1.1, the total annual usage for both buildings was multiplied by 20% to obtain the total annual usage for the candidate KC-135 off-aircraft parts. Table B-3 details the annual usage and cost of the masking materials.

Table B-3. Annual usage and costs of masking materials for baseline process.

Masking Materials	Usage in Bldg 3228	Total Annual Usage for All Off-Aircraft Parts[1]	Total Annual Usage[2]	Unit Cost	Total Annual Cost
Barrier paper	1 roll/month	24	5	$178.37	$892
12-inch plastic	1 roll/month	24	5	$47.38	$237
16-inch plastic	1 roll/month	24	5	$55.74	$279
1-inch tape	36 rolls/year	72	14	$13.69	$192
2-inch tape	24 rolls/year	48	10	$27.92	$279
3-inch tape	12 rolls/year	24	5	$41.06	$205
				Total	**$2084**

1 Assumed Building 2122 would be same usage as Building 3228.
2 Multiply annual usage by 20% to get total annual for candidate KC-135 parts.

1.1.4 Annual Utility Usage

The only utility information that OC-ALC personnel could provide that is specific to the stripping of off-aircraft parts was the water used to rinse the stripping chemicals from the parts. OC-ALC uses approximately 11 gal of rinse water per sq ft of area processed. There are approximately 97,800 ft^2 of area processed for the 676 candidate parts. The parts are rinsed 2.5 times for washing and chemical stripping. Therefore, the total rinse water used for chemical stripping of the candidate parts is approximately 2,700,000 gals per year (97,800 x 11 x 2.5 = 2,689,500). OC-ALC provided a unit cost of $0.0016/gal for rinse water, which calculated to be approximately $4,300 for the total annual cost.

1.1.5 Annual Waste Management

Wastewater

It was assumed that the disposed wastewater was equivalent to the rinse water that was used; therefore, it was assumed that OC-ALC disposed of 2,700,000 gal of wastewater per year. OC-ALC personnel provided a unit disposal cost of $0.0075/gal for wastewater, which calculated to be $20,250 for the total annual wastewater disposed.

Trench Cleaning

The trenches are cleaned in Building 2122 once a month, but there are no trenches to clean in Building 3228. The cost for the contractor to clean the trenches is approximately $20,000 per dock per month, and there are two docks being used, which calculated to be $40,000 per month or $480,000 per year. These docks are used both for full aircraft and for component part stripping. The stripping of off-aircraft parts, as noted in Section 1.1.2, consists of 33% of the total workload. The stripping of KC-135 candidate parts consists of 20% of the total off-aircraft workload, as noted in Section 1.1.1. Therefore, the cost of trench cleaning associated with the candidate parts calculated to be approximately $32,000 per year ($480,000 x 0.33 x 0.20 = $31,680).

Solid Waste

OC-ALC provided the actual hazardous waste disposal data and costs for calendar year 2007 for Buildings 2122 and 3228. It was assumed that the percentage of hazardous waste associated with the stripping of KC-135 candidate parts directly correlated to the percentage of chemicals used for stripping KC-135 candidate parts. As stated in Section 1.1.3, the annual chemical usage for the KC-135 candidate parts was calculated to be about 4400 gallons. The percentage of chemicals used for stripping candidate parts compared to the total chemicals used in Buildings 2122 and 3228 was then calculated to be 7% (4400 gals / 59,000 gals = 0.07, or 7%). Therefore, it was assumed that the stripping of candidate parts contributed to 7% of the following hazardous waste categories: filters, paint chips in water, paint chips from stripper, and contaminated rags and debris. Table B-4 details the annual disposal amount and the cost of the waste.

Table B-4. Annual hazardous waste disposal for baseline process.

Waste	Annual Disposal Amounts[1] (lb)	Candidate Parts Annual Disposal Amounts[2] (lb)	Unit Cost	Total Annual Cost
Filters	34,303	~2000	$0.88	$1760
Paint chips in water	120,434	~8000	$0.43	$3440
Paint chips from stripper	25,774	~2000	$0.26	$520
Contaminated rags and debris	67,170	~5000	$0.43	$2150
			Total	**$7870**

[1] Total for Buildings 2122 and 3228.
[2] Multiply "Annual Disposal Amounts" by 7% to get "Candidate Parts Annual Disposal Amounts," which is the total annual amount for candidate KC-135 parts. The amounts were rounded using appropriate significant figures.

1.1.6 Annual Environmental Compliance

As of 2004, there were 20 compliance sites associated with the de-painting process for the KC-135 weapon system in Building 2122, resulting in a cumulative adjusted environmental compliance (EC) cost of $31,100 per year. This compliance information was obtained from the OC-ALC Process Specific Opportunity Assessment (PSOA) document PSG WWYK-02-1030 "KC-135 Chemical Strip Procedure." Information was not provided for Building 3228; therefore, an assumption that the same number of compliance sites occurred in Building 3228 was made.

OC-ALC personnel stated that approximately 25% of the KC-135 workload processed in Building 2122 is for stripping KC-135 off-aircraft parts, while the remaining 75% of the KC-135 workload is processed in Building 3228. As previously noted in Section 1.1.1, approximately 25% of the KC-135 off-aircraft parts workload is for stripping the candidate parts for this cost assessment. Therefore, 6% (0.25 x 0.25 = 0.06, or 6%) of the KC-135 workload processed in Building 2122 and 19% (0.75 x 0.25 = 0.19, or 19%) of the KC-135 workload processed in Building 3228 is for stripping the KC-135 candidate parts.

The adjusted EC cost for the baseline process (i.e., stripping of the KC-135 candidate parts) was then calculated by multiplying the EC recurring cost (obtained from the PSOA) by the estimated contribution (calculated by multiplying 6% for Building 2122 and 19% for Building 3228 by the estimated contribution provided in the PSOA) for each of the compliance sites. The cumulative adjusted EC cost for the baseline process was calculated to be approximately $8000 per year (calculated by adding all the adjusted EC costs for the baseline process). Table B-5 shows the EC recurring costs.

Table B-5. Environmental compliance sites.

PSOA - KC-135 Chemical Strip Procedure
Tinker AFB (OC-ALC), Building 2122
PSG No. WWYK-02-1030
Date: 11/23/2004
Worksheet: WS-0

											Building 2122			**Building 3228**					
Compliance Sites						**KC-135 Chemical Strip Procedure**					**Baseline Process (Chemical)**			**Baseline Process (Chemical)**			**Alternative (RLCRS System)**		
Site Number	Base ID Number	Description	Site Owner	Type	Category	Environmental Compliance Recurring Cost ($/yr)	Risk Score	Estimated Contribution	Adjusted EC Cost ($/yr)	Adjusted Risk Score	Environmental Compliance Recurring Cost ($/yr)	Estimated Contribution	Adjusted EC Cost ($/yr)	Environmental Compliance Recurring Cost ($/yr)	Estimated Contribution	Adjusted EC Cost ($/yr)	Environmental Compliance Recurring Cost ($/yr)	Estimated Contribution	Adjusted EC Cost ($/yr)
WWYK0803	2405	Solvent Use	MABCCA	AIR	Major	$1825	720	100%	$1825	720	$1825	6%	$109	$1825	19%	$347	$1825	0%	$0
WWYK0804	2406	Solvent Use	MABCCA	AIR	Major	$1825	720	100%	$1825	720	$1825	6%	$109	$1825	19%	$347	$1825	0%	$0
WWYK0805	2412	Solvent Use	MABCCA	AIR	Major	$1825	720	100%	$1825	720	$1825	6%	$109	$1825	19%	$347	$1825	0%	$0
WWYK0806	2413	Solvent Use	MABCCA	AIR	Major	$1825	720	100%	$1825	720	$1825	6%	$109	$1825	19%	$347	$1825	0%	$0
WWYK1050	2052	Solvent Use	MABCCA	AIR	Major	$1825	720	100%	$1825	720	$1825	6%	$109	$1825	19%	$347	$1825	0%	$0
WWYK1059	2053	Solvent Use	MABCCA	AIR	Major	$1825	720	100%	$1825	720	$1825	6%	$109	$1825	19%	$347	$1825	0%	$0
WWYK1244		N/A	Basewide	EPCRA	Tier II RQ	$474	1152	25%	$118	288	$474	2%	$7	$474	5%	$23	$474	0%	$0
WWYK1699	LA0008-1723	Initial Accumulation Point	MABCCA8	HAZWASTE Mgmt.	N/A	$2239	3520	100%	$2239	3520	$2239	6%	$134	$2239	19%	$425	$2239	0%	$0
WWYK1700	LA0008-1104	Initial Accumulation Point	MABCCA8	HAZWASTE Mgmt.	N/A	$2239	3520	100%	$2239	3520	$2239	6%	$134	$2239	19%	$425	$2239	0%	$0
WWYK1701	LA0008-1142	Initial Accumulation Point	MABCCA8	HAZWASTE Mgmt.	N/A	$2239	3520	100%	$2239	3520	$2239	6%	$134	$2239	19%	$425	$2239	0%	$0
WWYK2457	LA0008-1503	Initial Accumulation Point	MABCCA8	HAZWASTE Mgmt.	N/A	$2239	4800	100%	$2239	4800	$2239	6%	$134	$2239	19%	$425	$2239	0%	$0
WWYK2459	LA0008-615	Initial Accumulation Point	MABCCA8	HAZWASTE Mgmt.	N/A	$2239	1920	100%	$2239	1920	$2239	6%	$134	$2239	19%	$425	$2239	0%	$0
WWYK2926	2401	Process Operations	MABCCA	AIR	Minor	$622	640	100%	$622	640	$622	6%	$37	$622	19%	$118	$622	0%	$0
WWYK2927	2403	Process Operations	MABCCA	AIR	Minor	$622	2016	100%	$622	2016	$622	6%	$37	$622	19%	$118	$622	0%	$0
WWYK2928	2410	Process Operations	MABCCA	AIR	Minor	$622	640	100%	$622	640	$622	6%	$37	$622	19%	$118	$622	0%	$0
WWYK3548		N/A	Basewide	EPCRA	Tier II RQ	$474	384	25%	$118	96	$474	2%	$7	$474	5%	$23	$474	0%	$0
WWYK3568		N/A	Basewide	EPCRA	Tier II RQ	$474	384	25%	$118	96	$474	2%	$7	$474	5%	$23	$474	0%	$0
WWYK3682	LA0008-1015	Initial Accumulation Point	MABCCA	HAZWASTE Mgmt.	N/A	$2239	4800	100%	$2239	4800	$2239	6%	$134	$2239	19%	$425	$2239	0%	$0
WWYK3685	LA0008-2009	Initial Accumulation Point	MABCCA	HAZWASTE Mgmt.	N/A	$2239	3840	100%	$2239	3840	$2239	6%	$134	$2239	19%	$425	$2239	0%	$0
WWYK3687	LA0008-2025	Initial Accumulation Point	MABCCA	HAZWASTE Mgmt.	N/A	$2239	960	100%	$2239	960	$2239	6%	$134	$2239	19%	$425	$2239	100%	$2239
		Initial Accumulation Point	MABCCA	HAZWASTE Mgmt.	N/A														
						Cumulative Adjusted EC Cost ($yr)			$31,082		**Cumulative Adjusted EC Cost ($/yr)**		$1865	**Cumulative Adjusted EC Cost ($/yr)**		$5905	**Cumulative Adjusted EC Cost ($/yr)**		$2239
						Cumulative Adjusted Risk Score				34,976									

Baseline Assumptions:
EC Recurring Cost and Risk Score obtained from PSOA WWYK-02-1030, Worksheet WS-0 "Process Description Information"
"Estimated contribution" for baseline process was calculated by multiplying the "estimated contribution" from the KC-135 stripping workload in Building 2122 by 25% (the percentage of workload for stripping KC-135 off-aircraft parts) and 60% (the percentage of KC-135 off-aircraft parts workload for stripping baseline candidate parts).
Therefore 15% of KC-1135 workload in Building 2122 is for the baseline process (a.k.a. off-aircraft candidate parts).

Alternative Assumptions:
100% decrease in chemical depainting of KC-135 candidate parts.
There will be a compliance site for disposal of filters, rags, gloves, etc. associated with RLCRS.
Assumed one compliance site for hazardous waste for an annual cost of $2239.

1.2 ALTERNATIVE DATA AND ASSUMPTIONS

The actual capital costs associated with the implementation of the RLCRS are provided in Table B-6. It is expected that the capital costs will be reduced if subsequent systems are implemented due to the expected reduction upfront engineering performed on the OC-ALC system.

Table B-6. Capital costs for Alternative Scenario.

Capital Costs				Total Cost
Equipment purchase	--	--	--	$819,982
Engineering (Building Research Infrastructure & Capacity [BRIC])	--	--	--	$1,027,471
Installation	--	--	--	$79,384
Training of operators	3 operators	8 hr	$236/hr	$5660
			Total Capital Cost	**$1,932,497**

Tables B-7 lists and quantifies the inputs and outputs associated with the RLCRS described above. The data and assumptions used in compiling the RLCRS usage and costs are detailed in the following subsections.

Table B-7. Process usage and costs for Alternative Scenario.

Labor	Number of People (3 shifts)	Total Time (hr/yr)	Unit Cost	Annual Cost
Labor hours	5	4040	$236.00	$2,152,000
Maintenance downtime	2	60	$236.00	$28,320
Laser safety training	5	1	$236.00	$1180
Materials	**Annual Usage**	**Unit**	**Unit Cost**	**Annual Cost**
Safety glasses	24	pairs	$2.50	$60
Half-face respirator	1	each	$19.95	$20
Filters (respirators)	4	pairs	$7.19	$30
Neoprene gloves	4	pairs	$0.79	$3
Cotton gloves	300	pairs	$0.99	$297
Aluminum tape	3	rolls	$27.92	$84
Pre-coat powder	1	bag (20 lb)	$600.00	$600
Activated carbon	1	each	$530.00	$530
Filter	4	set of 2	$1230.00	$4920
Gas for laser	2	cylinder	$2520.00	$5040
Laser preventative maintenance	2	each	$2500.00	$5000
Auto greasers (Gantry)	12	each	$46.00	$552
Dessicant cartridges	4	set of 2	$816.00	$3264
Utilities	**Annual Usage**	**Unit**	**Unit Cost**	**Annual Cost**
Electricity	72,400	Kilowatt hour (kWh)	$0.035	$2500
Waste Management	**Annual Disposal Amounts**	**Unit**	**Unit Cost**	**Annual Cost**
Filters	26	lb	$0.88	$23
Contaminated rags and debris	250	lb	$0.43	$108
Compliance				**Annual Cost**
Adjusted environmental compliance				$2200
			TOTAL Operating Cost	**~$2,206,731**

1.2.1 Annual Number of Parts De-Painted

It was assumed that the RLCRS would process the same number of parts that are processed for the baseline chemical stripping.

1.2.2 Annual Labor Requirements

Based on robotic safety requirements, an RLCRS will require two operators per shift for two shifts and one operator for one shift to perform nitpicking using a handheld portable laser. As shown in Table B-8, the total time to de-paint the targeted off-aircraft parts was calculated to be approximately 4040 hours per year for 52 KC-135 planes. The total process time for laser stripping was obtained from demonstrating the system on actual parts at OC-ALC. The loaded hourly labor rates, as provided by USAF representatives, were estimated to be $236 per hour. The total labor cost was calculated to be $2,152,000 ([1700 hr/person/yr x 2 people/shift x 2 shifts x $236/hr ≅ $1,600,000] + [2340 hr/person/yr x 1 person/shift x 1 shift x $236/hr ≅ $552,000]).

Table B-8. Laser coating removal process time.

Parts Identified	Number of Parts per Plane	Laser Strip Time (hr)	Handheld Laser Nitpick Time (hr)[1]	Total Laser Stripping Time (hr)
KC-135 aileron	4	8.0	4	12.0
KC-135 flaps	4	9.2	21	30.2
KC-135 rudder	1	6.5	4	10.5
KC-135 landing gear doors	2	3.3	12	15.3
KC-135 elevators	2	5.8	5	10.8
Total per Plane	13	33	45	78
Total per Year	676	~1700	~2340	~4040

[1] Assumed 5 mil coating thickness for estimate

The maintenance downtime was assumed to be for general maintenance issues with the equipment, such as changing the laser gas, changing the vacuum system filters and activated carbon, etc. It was assumed that the total downtime would equal about 5 hr per month and would affect only one shift, which calculated to be $28,300 of lost labor time (5 hr/mo x 12 mo/yr x 2 people x $236/hr ≅ $28,300).

The operators must fulfill 1 hr of annual laser safety training. The cost of this labor is $1180 per year (5 operators x 1 hr/yr x $236/hr ≅ $1180/yr).

1.2.3 Annual Material Usage

With the implementation of the RLCRS, it was assumed that there would be a 100% reduction in the chemical strippers associated with the baseline process.

Personal Protective Equipment

With the implementation of the RLCRS, it was assumed that there would be a 100% reduction in the annual usage of the following PPE associated with baseline process: face shields, rubber aprons, rubber boots, chemical shrouds, sleeves, wet suits, and fresh air hoods.

Operation of the RLCRS will require that generic safety glasses are worn when operators are outside the laser control room (as required by everyone in the building). When the operators are moving parts, cotton gloves must be worn. Finally, neoprene gloves and half-face respirators will be required during vacuum filter replacements. Table B-9 outlines the annual usage and cost of PPE for the alternative process, RLCRS.

Table B-9. Annual usage and costs of PPE for alternative process.

PPE	Replacement Time	Annual Usage (#/yr/person)	No. People	Total Annual Usage	Unit Cost	Total Annual Cost
Safety glasses	1 per 3 mo[1]	4	6	24	$2.50	$60
Neoprene gloves	1 per filter change[2]	4	1	4	$0.79	$3
Cotton gloves	1 per week	50	6	300	$0.99	$297
Half-face respirators[3]	1 per year	1	1	1	$19.95	$20
Respirator filters[4]	1 pair per filter change[5]	4	1	4	$7.19	$30
					Total	$410

1 Same replacement time that was used for the baseline process.
2 Assumed vacuum filters are changed four times per year (based on manufacturer recommendation).
3 The price for the half-face respirators was obtained from www.professionalequipment.com for Moldex Half Face Particulate Respirator P100 (Item#A407-8941).
4 The price for the half-face respirator filters was obtained from www.professionalequipment.com for Moldex P100 Particulate Filters (Item#A407-8940).
5 Assumed half-face respirator filters will be changed with each vacuum filter change-out.

Laser safety glasses will be required for use with the handheld lasers used for nitpicking the parts; however, it is a sunk cost because OC-ALC has already purchased those safety items when the handheld lasers were acquired.

Consumables and Preventative Maintenance

With the implementation of the RLCRS, consumables are required for the maintenance and operation of the laser system and the ancillary equipment, as well as the very minimal amount of aluminum tape masking that is required to ensure a smooth robotic motion over void spaces and brackets. Table B-10 outlines the annual usage and costs of the consumables for the RLCRS.

Table B-10. Annual usage and costs of consumables for alternative process.

Consumables	Replacement Time	Annual Usage	Unit Cost	Total Annual Cost
Precoat powder	1 bag/year	1	$600.00	$600
Activated carbon	1 per year	1	$530.00	$530
Vacuum filters	4 sets/year	4	$1230.00	$4920
Gas for laser	2 cylinders/year	2	$2520.00	$5040
Auto greasers	2 set of 6 per year	2	$276.00	$552
Desiccant cartridges	4 set of 2 per year	4	$816.00	$3264
Laser preventative maintenance	2 times per year	2	$2500.00	$5000
Aluminum tape	3 rolls per year	3	$27.92	$84
			Total	~$19,990

1.2.4 Annual Utility Usage

With the implementation of the RLCRS, it was assumed that there would be a 100% reduction in the rinse water associated with the baseline process.

The electricity used to run the equipment was considered. Table B-11 shows the calculations used to determine the total cost of the electricity use.

Table B-11. Annual electrical usage for alternative process.

Electrical Usage (Laser Process)	Volts	Amps	Power Factor (assumed)	Annual Operation Time (hr)	Total Annual Usage (kWh/yr)[1]	Unit Cost ($/kWh)	Total Cost
Chiller (BV Thermal) [2]	460	63	0.5	2000	30,000	0.0035	$1050
TEKA (Adapt)[3]	480	8	0.5	2000	400	0.0035	$14
Scanner Chiller (Bay Voltex)[3]	115	20	0.5	1570.4	2000	0.0035	$70
Laser (Rofin) [4]	480	112	0.5	785.2	20,000	0.0035	$700
Gantry/Scanner [3]	1440	20	0.5	1570.4	20,000	0.0035	$700
						Total Cost	**$2534**

1 Rounded to significant figure
2 Assumed operated 8 hr/day for 5 days/week for 50 weeks
3 Assumed operated only when stripping parts
4 Assumed electrical usage only when laser beam is actually "on"

1.2.5 Annual Waste Management

With the implementation of the RLCRS, it was assumed that there would be a 100% reduction in the wastewater associated with the baseline process.

<u>**Solid Waste**</u>
With the implementation of the RLCRS, it was assumed that there would be a 100% reduction in all hazardous waste associated with chemical stripper used in the baseline process. However, the hazardous waste disposal associated with the alternative process is composed of filters (i.e., vacuum filters and respirator filters) and other consumables (i.e., gloves, aluminum tape, rags,

etc.). Table B-12 outlines the estimated annual disposal amount and cost for the alternative process.

Table B-12. Annual disposal amount and costs for alternative process.

Waste	Annual Amount	Unit Weight (lb)	Total Weight (lb)[1]	Unit Disposal Cost[2]	Annual Disposal Cost
Vacuum filters	8 filters	3	24	$0.88	$21.12
Respirator filters[3]	8 filters	0.2	2	$0.88	$1.76
Activated carbon[4]	1 lot	10	10	$0.43	$4.30
Precoat powder	1 bag	20	20	$0.43	$8.60
Auto greasers[4]	12 units	1	12	$0.43	$5.16
Dessicant cartridges[4]	8 cartridges	1	8	$0.43	$3.44
Rags, tape, gloves[4]	1 lot	200	200	$0.43	$86.00
				Total	**~$130.00**

1 Rounded values
2 Unit disposal costs based on disposal costs of baseline waste
3 Assumed the unit weight of 0.2 lb
4 Assumed the unit weight, based on best guess

1.2.6 Annual Environmental Compliance

With implementation of the RLCRS, it was assumed that there would be a 100% decrease in chemical de-painting of candidate parts. However, the alternative process will require at least one compliance site to dispose of the filters and other consumables associated with the system. It is unknown at this time what the EC recurring costs are associated with one compliance site. As shown in Table B-5, it was assumed to be about $2200 per year based on an “initial accumulation point” for a hazardous waste management site.

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